Escape of Superheated Upsilons from the Quark Gluon Plasma

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Abstract

The properties of heavy quark systems change if they are placed in a medium other than the low energy vacuum. In a hot Quark Gluon Plasma J/Ψ particles will melt and not exist as resonant states. Υ's, however, because of their smaller size and the dominance of the Coulomb potential, will still form as $Q\bar{Q}$ bound states but their properties will shift. In particular the Υ mass may be shifted upward by over 100 MeV. If such excited states manage to escape from the plasma as a superheated particle, they may serve as a diagnostic of the plasma in which they originated. We propose that such a scenario is possible and that hot Υ's will form and escape, thereby providing us with crucial information about the Quark Gluon Plasma.

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1 Introduction

As the hunt for the Quark Gluon Plasma (QGP) heats up, the search for a clean diagnostic signal becomes pressing. The properties of heavy Quarkonium have figured prominently, and promisingly, as a signal for the formation of the QGP. Over a decade ago the melting of the J/Ψ particle in a plasma was suggested [1] as a signal for QGP. However, the subsequent observation of J/Ψ suppression in heavy ion collisions was the result of nuclear absorption rather than melting [for a review of the field, see [2]. More recent observations [3]are more indicative of a melting effect [4, 5, 6] although, again, the interpretation is not unambiguous [7, 8, 9].

The advent of RHIC and LHC may give us the opportunity to clearly see this melting effect. The higher energies available to collide larger nuclei will produce hotter, more dense material. In addition we expect production of heavy Upsilons [see, e.g., [10]]. In this note we propose that the properties of these heavy Quarkonium may expose the existence of the QGP and help in exploring its properties.

The original suggestion for quarkonium melting in QGP was based on the idea that the confining inter quark potential would be screened in the plasma and that sufficient screening would liberate the quarks. While recent discussions of J/Ψ suppression rely on a more microscope description of gluon quarkonium interactions, the original picture is more immediately transparent and suggestive of further effects. Our discussion will be framed in the context of a macroscopic picture of the QGP, and its inherent screening properties.

Fragile quarkonium such as J/Ψ, are readily disrupted by screening. The more robustly bound Υ will maintain its integrity as a bound state in the plasma but will have its properties, such as its binding energy and hence its mass, shifted. Since the screened Υ will still be small, comparable in size to the unscreened J/Ψ, it will not be highly interactive with the hot nucleons surrounding, and replacing, the cooling plasma. It thus has a reasonable chance of escaping relatively unscathed from its fiery surroundings and decaying in a detector with a mass different from its unscreened, normal, brethren. This mass shift will be a noticeable signal, and possible diagnostic of the Quark Gluon Plasma. The remainder of this note will be a justification of the above scenario.

2 Hot Upsilon

Debye screening in a conventional plasma is well established. Analogous effects are expected in the QGP. A heavy Q$\bar{Q}$ in the medium of the QGP will still experience an attractive potential but both the short distance, Coloumb, and the long distance, linear, pieces of the potential will be screened. If we assume the zero temperature, zero baryon density, interquark potential is described by the phenomenological addition of the long range confining potential and short range Coulomb potential we have the Cornell potential

$$V = \sigma \ln r - \frac{\alpha}{r} \tag{1}$$

We expect that the Coulomb, perturbative piece will undergo Debye screenning and behave like

$$-\frac{\alpha}{r} e^{-\mu r}, \tag{2}$$

with μ the screening mass. The Debye screening radius is $1/\mu$. The linear part of the potential should also be screened and we addopt the suggestion of [11]

$$\frac{\sigma}{\mu}(1 - e^{-\mu r}), \tag{3}$$

leading to the screened QGP potential

$$V(r, \mu) = \frac{\sigma}{\mu}(1 - e^{-\mu r}) - \frac{\alpha}{r} e^{-\mu r} \tag{4}$$

Evidently the confining character of the potential is gone, just as we anticipated. However, we still have an attractive potential which can bind a $Q\bar{Q}$ pair into quarkonium if the quarks are sufficiently massive. It is a dynamical question which states will bind and which won't. Even for moderately high values of T, the screened potential (4) will bind $b\bar{b}$ into a bound "hot" Υ with properties different from the properties, determined by (1), for the $T = 0$ Υ. This contrasts with the case of J/Ψ which readily loses its binding and melts. This was the initial motivation for the proposal that J/Ψ suppression would be a signal for the QGP. The fact that a modified Υ may survive offers the opportunity to study some properties of QGP in more detail.

In order to study the modifications introduced by screening we need an acceptable $T = 0$ potential. By now this is a routine task and has been done numerous times. We use here the values presented in [12]:

$$\alpha = 0.470, \quad \sigma = 0.186 Gev^2, \quad m_b = 4.753 Gev \tag{5}$$

We now ask what happens to the bound states when the screening turns on as T increases. In our simple model all the T dependence is contained in μ. At present the only means of determining this T dependence are via lattice calculations. A simple characterization of these results which has been used in the literature [13] is

$$\frac{\mu(T)}{T_c} = 4\frac{T}{T_c} \tag{6}$$

In what follows we will mostly work with μ. The quantities we are most interested in are the mass and the size of the bound states. The mass shift will serve as a marker for the unusual environment in which the bound state forms while the size will be a useful guide to the ability of the shifted superheated state to slip through the hot nuclear environment and escape. Using the above parameters and inserting them in Eq(4) we find the following masses and sizes for the $\Upsilon(1S)$:

$\mu(Gev)$	$Mass(Gev)$	$r(fm)$
0.0	9.45	0.23
0.6	9.60	0.29
0.8	9.62	0.33
1.0	9.64	0.41
1.2	9.64	0.58
1.4	9.63	1.03

(7)

The mass of the $\Upsilon(1S)$ is seen to increase as μ (and T) increases from 0 to $1GeV$. The size of the state also increases but remains small. At $\mu = 1.0GeV$ the size is comparable to the $T = 0$ size of the J/Ψ, while at $\mu = 0.6GeV$ the hot $\Upsilon(1S)$ is considerably smaller than a cold J/Ψ.

The mass shift is easy to understand. The $b\bar{b}$ quarks in the Υ primarily feel the influence of the Coulomb part of the potential. They are so close together that they are hardly aware of the confining part and thus hardly notice its disappearance at high T. It is this insensitivity to the confining potential that is responsible for the survival of the Υ at high T. If the Coulomb potential is screened, its negative contribution to the bound state energy is weakened increasing the mass and the radius. If this superheated state escapes and can be observed it will indicate the formation of a macroscopic medium with a screened potential. The most optimistic scenario would allow this shifted mass to serve as a thermometer of the original QGP.

We also computed the mass and size for the first excited state, $\Upsilon(2S)$. This state melts as μ approaches $0.6GeV$. The $2S$ is a larger state at $T = 0$ and is sensitive to the linear potential. As this potential is screened the binding becomes more precarious, the mass drops, the radius increases and the state eventually melts. This is very similar to what happens to the J/Ψ and in fact both the $\Upsilon(2S)$ and the J/Ψ melt at a similar T.

3 Fate of Hot Upsilons in Heavy Ion Collisions

In order to study the formation of hot Υ we begin by looking at the case of a heavy ion collision which produces a $Q\bar{Q}$ system at $t = 0$, at rest in the lab (CM)frame. After a time t_0, a large (effectively infinite) QGP, at temperature T_0, forms. The QGP will begin to cool. We assume the cooling rate is related to the expansion time as given by longitudinal isentropic expansion equation

$$s(t_0)t_0 = s(t)t \tag{8}$$

where s(t) denotes the entropy density at time t.

There are three temperatures that are of significance:

a) We define T_m as the melting temperature above which the bound $Q\bar{Q}$ state can no longer form. In our model it is the temperature for which the potential (4) no longer supports bound states. For the $\Upsilon(1S)$ this occurs for $\mu \simeq 1.44GeV$. If we use eq.(5) this corresponds to $T_m \simeq 360MeV$.

b) T_c is the transition temperature above which a QGP can form. Current estimates put $T_c \simeq 150MeV$. Below T_c we have a hot hadron gas.

c) T_0 is the initial temperature of the plasma. We assume that $T_0 > T_c$.

The corresponding times are also of significance:

1) t_0 is the time of formation of the plasma,

2) t_m is the time at which the plasma cools below the melting temperature T_m and

3) t_c is the time at which the plasma cools below T_c and becomes a hot hadronic gas.

These times acquire their significance when compared to the formation time t_f, the time it takes for the initial $Q\bar{Q}$ pair, at rest, to form a quarkonium bound state. A simple model for t_f is the time required for the two quarks, forming a specific quarkonium state, to separate a distance R equal to the size of the corresponding state. The velocity of separation is the quark velocity as given by the potential model for that state, so $t_f = R/v$.

If $T_0 > T_m$ but $t_f < t_m$, by the time the quarks separate a distance R the medium will still be hot enough that quarkonium will not form and the quarks will continue on their separate ways. We say the quarkonium has melted rather than formed and hence will not be produced. If $t_f > t_c$ the quarkonium will form as a regular $T = 0$ quarkonium state of unmodified mass. Of most interest to us is $t_m < t_f < t_c$ when a quarkonium will form but will not have its traditional $T = 0$ properties. These properties (e.g. mass and wave function) will be determined by the screened potential appropriate for some T, with $T_m > T > T_c$.

T_m and t_f are fixed by the interquark potential and T_c is a fundamental property of the QGP. Thus, for $Q\bar{Q}$ at rest, the production of hot quarkonium is determined by the initial T_0. If

$$t_m < t_f < t_c \tag{9}$$

hot quarkonium states with properties different from $T = 0$ states are produced.

Most $Q\bar{Q}$ are, however, not produced at rest with respect to the QGP rest frame. They will have momentum $\mathbf{P}$ and we must account for the relativistic time dilation when computing the relevant t_f. The formation time in the QGP rest frame for a system of mass M and moving with momentum $\mathbf{P}$ is

$$t'_f = t_f \sqrt{1 + \frac{\mathbf{P}^2}{M^2}} \tag{10}$$

Hence eq.(9) is replaced by

$$t_m < t'_f < t_c \tag{11}$$

In order to relate the times and temperatures we need an explicit expression for the entropies appearing in Eq.(8). As usual we take the simplest reasonable form, i.e. the entropy for a free gas:

$$s(T) = const \cdot T^3 \tag{12}$$

Combining Eqs.(8),(9),(10) and (12) we find that only those states produced with momentum in the range

$$\Big(\frac{t_0}{t_f}\Big)^2 \Big(\frac{T_0}{T_m}\Big)^6 - 1 < \Big(\frac{\mathbf{P}}{M}\Big)^2 < \Big(\frac{t_0}{t_f}\Big)^2 \Big(\frac{T_0}{T_c}\Big)^6 - 1 \tag{13}$$

will form as hot quarkonium.

When the initial temperature T_0 is lower than T_m, the lower limit for the momenta is obtained from the restriction $t_0 < t'_f$, that is we exclude the states formed before the QGP sets in.

For $\Upsilon(1S)$ t_f is 0.76fm at $T = 0$ and 1.16fm at $T = T_c$, while T_m is 360 MeV. We estimate the parameters t_0 and T_0 based on the expectations at RHIC. At RHIC the plasma should form at $t_0 \simeq 0.2fm$ [14] while the initial temperature will be $T_0 \simeq (2-3)T_c$.

Therefore the LHS of eq.(13) will be less than zero and the lower limit on P is P>0. This just means that all Υ's are produced after the plasma forms. For the upper limit we use the formation time in the hot plasma $t_f \simeq 1.16fm$ and find an upper limit in the range of 9-43 GeV.

We now must ask what percentage of produced Υs will have momentum in this range.

Assume that the production rate for Upsilons falls off exponentially with the transverse momentum P_T as

$$exp\Big[-\lambda\sqrt{\mathbf{P}_T{}^2 + M^2}\Big] \tag{14}$$

Here M is the $\Upsilon(1S)$ mass and we take λ to be few Gev similar to that for ordinary hadrons. We can then calculate the fraction of produced Υ's which are hot as the P_T integral of (14). Because of the steep fall off of this function, we see that practically all Υ's are produced within the plasma, i.e. they are hot.

If hot Υ's form in a QGP as outlined above, they will be interesting only if we know of their existence. The most promising signal of this existence is if some of the Upsilons escape from the plasma and its surrounding fireball. Since the hot Υ is still small, a geometric picture of scattering would imply a reasonable likelihood of escape.

We picture a large, spherical plasma wich cools down to a hot hadron gas at time t_c. At this time all the hot Υs will be immersed in the hadron gas where they can scatter and cool down or be disrupted. We can quantify this in a simple absorption model. We follow the treatment of Karsch and Satz [15].

The survival probability for the Υ entering the hadron gas at time t_c and surviving until time τ when the gas has cooled down sufficiently to be non-interacting is

$$S(\tau) = exp\Big[- \int_{t_c}^{\tau} dtn(t)\sigma \; \Big] \tag{15}$$

n(t) is the density of the medium and σ is the inelastic cross section for $\Upsilon(T)$ in the hadron gas. τ is the time it takes for the hot hadron gas to become so cool and dilute that no further interactions are likely. We take this "freeze out" conditions to occur when the energy density ϵ is $0.3GeV/fm^3$. If we continue to assume isentropic longitudinal expansion

$$n(\tau)\tau = n(t_c)t_c \tag{16}$$

we find that

$$S(\tau) = \Big[\frac{t_c}{\tau}\Big]^{\kappa}, \qquad \kappa = n_c t_c \sigma \tag{17}$$

The ideal gas equation of state for quarks and gluons when combined with isentropic longitudinal expansion relates $n(t)$ to the energy density ϵ to the power 3/4 so that

$$n(t) \propto (\frac{2}{3}\epsilon)^{3/4}, \qquad t_c/\tau = (\epsilon/\epsilon_c)^{3/4}, \qquad t_c/t_0 = (\epsilon_0/\epsilon_c)^{3/4} \tag{18}$$

Consistent with our use of $T_c \sim 150$ Mev we find $\epsilon_c \sim 1$ Gev/fm^3 and arrive at the survival probability

$$S(\tau) = [0.3]^{(3/4)\cdot\sigma\cdot(2/3)^{3/4}\cdot\epsilon_c^{3/4}\cdot t_c} = [0.3]^{(3/4)\cdot\sigma\cdot(2/3)\epsilon_0{}^{3/4}t_0} \tag{19}$$

The crucial unknown in this equation is the cross section for a hot Υ interacting with hadrons. A geometric picture implies that this cross section will be proportional to the square of the size of the Υ. The hot Υ, at $T = 150MeV$ ($\mu = 0.6GeV$) is larger than its cold prototype but is still quite small. From eq.(7) we see that it is some 60% of the size of J/Ψ, wich is usually taken to be of order (1/2)fm. The hadronic cross section should then be considerably smaller than the hadronic cross section for J/Ψ. Reasoning based on the heavy quark limit of cross sections bears out this estimate [16, 17, 18].

Therefore we estimate a cross section σ of 0.5-1 mb. Putting this value into eq.(19) and using $\epsilon_0 \simeq$16-81 GeV/fm^3, corresponding to $T_0 = (2-3)T_c$, we find that roughly 30-80% of the hot Upsilons that emerge from the plasma will survive their traversal of the hot hadron gas and be candidates for observation and detection.

From eq.(14) we estimated that almost all of the Υs produced will be hot and that of these about 30-80% will escape hadronic interactions, so roughly 30-80% of produced Υs will be superheated. Since these superheated states have their masses shifted by$\sim$ 150 MeV it should be possible to observe them as an enhanced shoulder on the high energy side of the Υ peak in heavy ion collisions. This will be a strong signal that a hot, screening medium has been produced. Studying the details of the mass distribution, especially in conjunction with J/Ψ and $\Upsilon\prime$ suppresion, should provide insight into the nature of the medium responsible for the mass shifts.

4 Conclusions

The arguments we have presented are very qualitative, similar to the original arguments in favor of J/Ψ suppression. Nevertheless the strong physical pictures that underlies these arguments leads us to propose a search for superheated Υs as a signal for Quark Gluon Plasma formation.

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